Investigation of the Effect of Laser on the Breakdown Strength of Atmospheric Air with Lightning Impulse Voltage

A Thesis Submitted
in Partial Fulfilment of the Requirements
for the Degree of

Master of Technology

by

SUDHIR KUMAR SINGH

to the

DEPARTMENT OF ELECTRICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY KANPUR

May, 2001

8-5-2001

Certificate

It is to certify that the work contained in this thesis entitled "**Investigation of the effect of Laser on the Breakdown Strength of Atmospheric air with Lightning Impulse Voltage**" by **Sudhir Kumar Singh** (9910480) has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

May 8, 2001

(Dr. Ravindra Arora)
Professor
Department of Electrical Engineering
Indian Institute of Technology
Kanpur - 208016
India.

Dedicated

to

Dr. Ravindra Arora

Acknowledgement

It is with extreme respect and warm feelings that I wish to express my deep sense of gratitude and great indebtedness to Dr. Ravindra Arora, for his constant inspiration, affectionate guidance and encouragement throughout the course of my work. I feel indebted for initiating me into this problem and provided the necessary education and help at every step and indeed fortunate to work under his able supervision.

I acknowledge the help, guidance rendered by Dr. Bansilal of Laser Department and the discussions with him really help a lot in my work. I am thankful to all my teachers from IITK for gracefully sharing their valuable knowledge.

My sincere thanks to Mr. S. V. Ghorpade and all other staff members of the high voltage laboratory, for their full cooperation and prompt assistance during the experiments. I also thanks to my friends Halder, Jangid, Mukul and Deba for their helpful company during my course of work.

I feel fortunate to join an extremely coherent batch for my masters. I remember billiards club members and all my batch mates for their lively company during my stay at IIT Kanpur.

Last, but not the least I wish to thank my parents, sisters Pratibha, Bandna and Jyoti for their source of inspiration and moral support throughout my career. Without them nothing would have been possible.

Sudhir K Singh

Name of student	: **SUDHIR KUMAR SINGH**
Roll No.	: **9910480**
Degree for which submitted	: **M. Tech.**
Department	: **Electrical Engineering**
Thesis Title	: **Investigation of the Effect of Laser on the Breakdown Strength of Atmospheric Air with Lightning Impulse Voltage.**
Thesis Supervisor	: **Dr. Ravindra Arora**
Month and Year of Submission	: **May, 2001**

Abstract

Laboratory investigations were carried out to study the effect of laser radiation on the breakdown strength of the air with lightning impulse voltage. A big bowl shape electrode prepared with aluminum simulated a cloud. Experiments were performed with two electrode configurations, one the Cloud-rod electrode and the other cloud-needle with lightning impulse voltage generated by impulse generator. Probability of breakdown, time required for the propagation and propagation velocity were studied the measured results with the application of laser and without laser have been compared. A theoretical investigation has been made to estimate the minimum laser intensity required to ionize the atmospheric air. During the course of experimental investigations accurate measurement of magnitude of impulse voltage and propagation time were accomplished with the help of digital oscilloscope.

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c	Speed of light (cm/s)
d	Mirror separation in resonant cavity
E	Electric field (V/cm)
E_1, E_2	Energies of an atom (eV)
E_I	Ionization potential (eV)
I	Power density of laser (W/cm^2)
n	No. of photons
N	Density of neutral atoms in a gas (cm^{-3})
N_l	No. of atoms in lower state
N_u	No. of atoms in upper state
p	Pressure of the gas (Torr)
P_A	Probability of spontaneous emission
Q	Quality factor
t_p	Propagation time
t_s	Statistical time lag
U_b	Breakdown voltage (kV)
τ_e	Time spend by an atom in excited state
τ	Pulse width of laser beam (s)
λ	Wave length of laser (μm)

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1. Introduction

1.1. Introduction

Although lightning has been harmful to mankind. It has been able to maintain ecological balance of electric charge. The effect of lightning can have serious consequences on human activities Its cost in human lives and the devastation it can produce, year after year, over the world are a few examples of this natural power Lightning can also disrupt industrial processes by causing recurrent power outages and significant equipment failures besides the destruction caused by blasts.

The study of lightning has been hampered because of the erratic nature of lightning stroke. Since it is very difficult to know exactly when and where the lightning stroke will take place, many years are required to collect data on lightning stroke of a particular location. Damage can be caused to an airplane or rocket flying in the vicinity of electrified clouds if it inadvertently triggers lightning The impact of thunderstorm also affects aircraft and space shuttles despite careful shielding. In an incident, the electric field in the cloud was too weak to initiate lightning by itself, but strong enough to sustain lightning after it was triggered by the rocket. [18]

For the protection of airborne objects as well as sensitive ground installations, such as power plants and mining operations, it is important to be able to identify a marginally electrified cloud and discharge it. A commonly used method to trigger lightning is to fire small rockets pulling up ground wires toward the thundercloud. The speed of rockets, however, in no way can compete with the charge motion and subsequent screening process. It is also obvious that the rockets cannot be launched on a semi-continuous basis. Instead, the most appropriate timing has to be chosen by monitoring the field under the cloud. The success rate for this method to be able to discharge the cloud is generally about 60% If the goal is to discharge a cloud, rather than trigger occasional lightning for analysis, then a more reliable, faster method, which could be applied at a higher repetition rate, is desirable. [19,21,22]

The idea of using laser to trigger lightning crossed the mind of scientists in the 70's. Recent advances of laser suggest the possibility of laser-triggered lightning When a high power laser beam is focused in air, a high degree of ionization is produced at the focus. This is well known phenomenon called *optical breakdown.* [20] If the power of the laser is high enough, a chain of air-breakdown plasmas are produced along the laser beam. To produce gas (air) ionization, it requires very high light intensities, of the order of 10^{12} W cm^{-2}. The laser - triggered lightning technique is promising for the protection of power transmission systems or any other installations and the study of natural lightning.

1.2. Scope and Objective of the Thesis work

Air is the dielectric, most easily available in the nature. The dielectric strength of gas depends upon many factors like pressure of the gas, moisture and above all the number of free electrons present in the gas. These free electrons present in the air are due to ultraviolet rays and cosmic rays coming from Sun

If laser of high power is focused in the air, it emits photons, which ionizes the molecules present in the air. Higher the number of ionized particles present in the medium, smaller will be the breakdown voltage of the medium In other words, we can say, for the same gap distance we need less voltage for the breakdown. This is the concept, which is taken into consideration in the present work The objective of the thesis work is

- Investigation of the effect of laser on the breakdown voltage of the given gap distance.
- Minimum laser intensity needed for guiding lightning
- Effect of the laser on the propagation velocity
- Effect of the laser radiation on the propagation time of the lightning impulse.
- Minimum laser power density required to ionize the air.

1.3. Organization of the thesis

- Chapter 2 presents details on lightning phenomena Characteristics of lightning strokes are described. Breakdown strength of air with lightning impulse voltage is also considered briefly

- Chapter 3 deals with the classification of lasers and the theory behind lasers. The operation of lasers also covered in brief Applications of lasers in various fields also discussed

- Chapter 4 presents the theoretical study of air ionization with the laser radiations At different wavelengths of laser, the ionization of atmospheric air is investigated

- Chapter5 presents the experimental set-up and provide details about equipment used with the impulse generator with their specification. Electrode configurations used are described with electrode dimensions. The atmospheric conditions during experiments and set-up photograph also included.

- Chapter 6 presents experimental investigations and breakdown voltage, propagation time and propagation velocity with fixed gap distance between two electrode configurations for impulse waveforms of either polarity.

- Chapter 7 includes the conclusions and scope for future works

2. Nature of Lightning

2.1. Lightning Phenomena

Physical manifestation of the lightning has been noted since ancient times but the understanding of the lightning has been relatively poor. Although Franklin carried out experiments on lightning in 1744 - 1750 but most of the knowledge has been obtained in last 50 years. Study of lightning became significant when electric transmission lines had to be protected against the lightning strokes.

The phenomenon of lightning is now generally accepted to be nature's means of keeping "Global Electric System' balanced. A widely accepted view of the global electric system is that the earth and the lower ionosphere are two highly conductive surfaces separated by layer of air as insulation. Thus it forms a large condenser with some leakage. The lower ionosphere (layer within a height of 50 -75 kms) and the earth surfaces are highly conductive. Over fair weather areas there is a downward transfer of the positive charge, which tends to reduce positive potential of ionosphere and to neutralize the negative charge on the earth. Within global system lightning discharge is instrumental in transferring positive charge upward at a rate sufficient to sustain a balanced dynamic system; that is, the regular current flow between the positively charged ionosphere and negatively charged earth is controlled and maintained by global thunderstorm activity. [5]

Over the total earth's surface as many as 2000 thunderstorms are continually in existence, within ionosphere and between ionosphere and earth. Active thunderstorms with lightning discharge a charge at an average rate of 20 C every 10 seconds, which is equivalent to approximately 2 A of steady current. The capacitor formed by air between lower ionosphere and earth's surface is more or less at a steady potential of 300 kV. Earth being negative and ionosphere being positive the average current between the two is of the order of 1500 A, this would indicate the existence of 700 to 800 active thunderstorms, and even more if minor storms are also taken into consideration. The current density at the earth's surface is estimated at 3×10^{-12} A/m^2. These figures are average values and have

been arrived at using measurements of air conductivity and potential gradients. The steady electric field at the earth's surface is about 3 V cm in fair weather conditions and during thunderstorms development this can rise to 500 to 600 V cm beneath the thunderclouds and to much higher values near ground level below a stepped leader. In view of the above, it must be appreciated that a lightning discharge must transfer to earth negative charges Thus the lower end of the cloud will be negatively charged, which induces a positive charge on the ground. [1, 15]

During thunderstorms, positive and negative charges are separated by interplay of air currents, ice crystals in upper part of the cloud, and the rain in the lower part. Electrically a thundercloud may be regarded as a charge separation device or electric generator satisfying the needs of "global system". This process is subjected to many theories. A few observable facts are of interest: clouds are negatively charged with a layer of positive charge at the top, which is typically 9 - 12 kms above the grounds surface, the cloud base may be as low as 150m. [1, 2, 14,16]

A lightning stroke is first established in the form of a 'stepped leader' whish starts in the cloud region where a local charge concentration causes the potential gradient to reach a very high value. For dry air, the breakdown strength of the atmospheric air is high, but in clouds like conditions, it may reduce considerably A leader discharge moves rapidly in steps of about 50 m in a highly ionized space with a velocity of about 10 cm/µs and above. In the process it deposits a negative charge along its path. As the leader head approaches the ground, positive charge induces in the target area intensify. However point of strike remains undermined until leader has arrived at a suitable striking distance from the surface. It is well known that the field configuration determines the breakdown strength of air at this instant. The strike point on the earth depends upon the potential gradient below the leader channel and distribution of the space charge in the atmosphere besides the condition of the atmospheric air this implies that not only high objects and elevations above the ground receive the stroke but also the plains and even objects in the valleys between the mountains are vulnerable. At this stage, a short positive streamer may rise from the earth called the return stroke. It preferably appears at the location of high field intensity for example, sharp metallic objects. The return stroke develops as an intense luminous discharge, which we see

as a 'flash' or the 'instable leader'. After the first return stroke, it is usual for another region of the cloud to provide sufficient charge for a second stroke or several more, separated by intervals of 10 to 20 msecs. The average current in the lightning stroke is about 20 kA but in exceptionally intense storms it can exceed even.100 kA. Average charge released per flash is about 25C. [1, 4]

2.2. Lightning Stroke Characteristics

Extensive work has been carried out to obtain the lightning strokes characteristics since 60's and early 70's. [4,5,6,12] Uman compiled in details the quantitative aspect of usual negative cloud to positive earth lightning strokes. Few decades back, one of the bottle neck while working on lightning was the non availability of the impulse generators and the measuring equipments. Bandwidth of the measuring equipments available was not sufficient to analyze the characteristics of the lightning currents.

Detailed investigations were carried out at the " Pessenberg Tower " in south Bavaria, Germany in which currents wave forms of actual lightning were recorded and spectral analysis was carried out. [17]

The standard lightning voltage impulse is defined as 1.2 50 μs by IEC 99. It also laid down the standard tolerances as ± 20 % on the front time and ± 30 % on the time to half value. [3] A standard waveform of lightning impulse voltage with either polarity is shown in fig. 2.1 and 2.2,drawn with the help of plotter.

The energy in a typical lightning discharge was calculated taking the value of 10^7 V for the breakdown voltage between the cloud and the ground and assuming a total discharge of 20 C. The energy released is 20×10^7 J, or about 55 kW - hr. The crest current per stroke, which may rise in 1 or 2 μs and fall to half its value in 40 to 50 μs, is about 20 kA on the average, but it can reach several times this value in an intense storm. The energy of the flash dissipated in the air channel is expanded in several processes. Small amount of energy produce dissociation of molecules, ionization, excitation of the earth's magnetic field. About 1 % is spent for kinetic energy of the channel particles, and 0.4 % in radiation. A large part of the energy, about 98 % is consumed in the sudden expansion of, the air

channel. Some fractions of the total clouds heat and, at times, fracture of the earth or the grounded object that is struck. In general lightning returns to the global system the heat energy that originally created the charged clouds helping to maintain the energy balance. [1]

2.2.1. Breakdown Strength of air with Lightning Impulse

Breakdown strength of air is complicated phenomenon, which not only depends upon its atmospheric conditions but also upon the field configuration determined by the shape and size of the electrodes and the gap distance. Besides the breakdown strength also depends upon the type of the voltage applied and its polarity. For long air gaps where an extremely nonuniform field prevails, the breakdown strength when measured with ac and long duration impulse voltage depends upon the type and extent of stable PD, which precedes the breakdown.

However, the phenomenon of the breakdown with lightning impulse is different because of short rise time of the impulse as well as its small duration no stable PD are able to take place in this case. In these cases an instable leader followed by an arc directly accomplishes breakdown. Thus in case of lightning the probability of breakdown depends upon a statistical time lag, which is the function of the magnitude of the voltage applied, and the availability of the initiatory electrons, whish in turn depends upon the size of the electrode surface area. The laboratory experiments have revealed that the breakdown strength not only depends upon the irradiated condition of the electrodes but also upon the pre-ionization extent available in the gas. This is the reason, why power system installation attracts lightning most. [1]

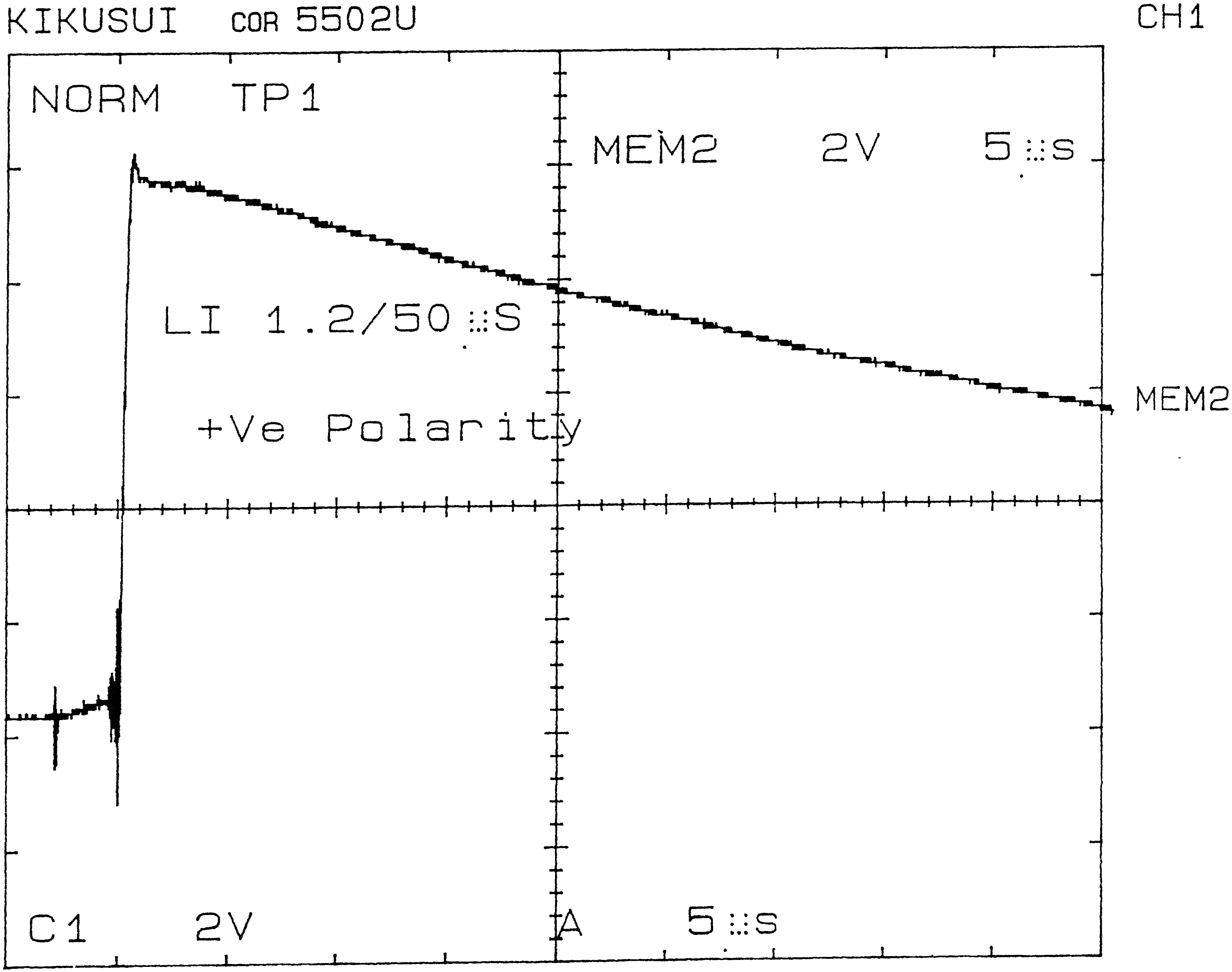

Fig. 2.1. Plot of positive polarity impulse voltage with plotter

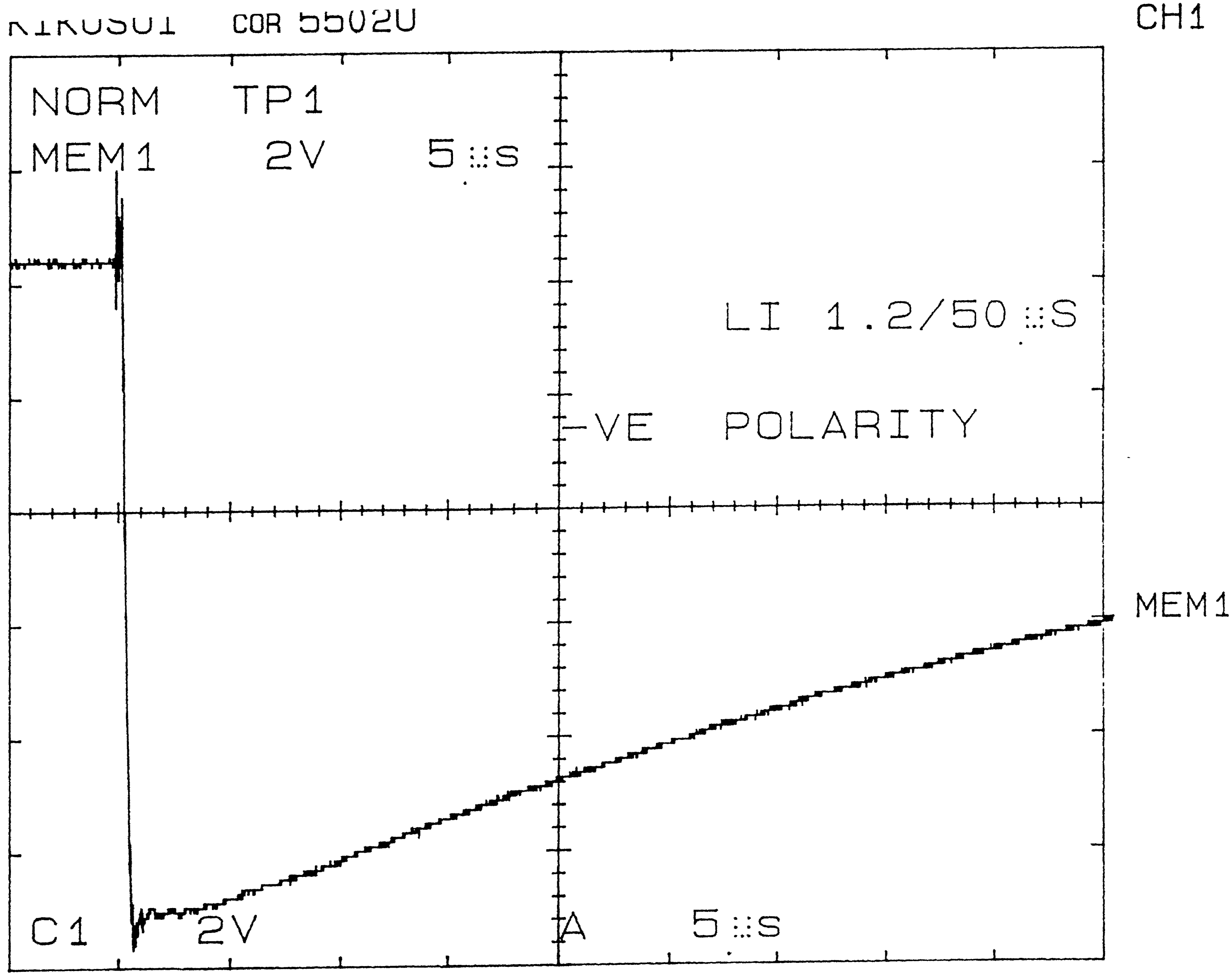

Fig.2.2. Plot of negative polarity impulse voltage with plotter

3.1. Introduction

The acronym LASER stands for Light Amplification through Stimulated Emission of Radiation and is a follow-up to its predecessor MASER where M stands for Microwaves. Although laser can be configured as an amplifier but from the common usage of the term Laser, we mean an optical oscillator, which like its radio frequency counterpart generate nearly monochromatic light. Emission and absorption of light by atoms and molecules are quantum processes. Max Planck in 1900 suggested that electromagnetic radiation is quantized. A quantum of energy is called photon.

Neil Bohr in 1913 postulated that absorption and emission of light by an atom is also quantized. If E_1 and E_2 represent energies of an atom before and after emission (absorption), then

$$E_2 - E_1 = \pm h\nu$$

An atom can be found in any of a large number of quantized energy states These energy states are labeled by the so-called quantum numbers Light is emitted and absorbed by atoms during their transition from one energy state to another When an atom goes from its normal state (also called ground state), which is a state of minimum energy to a higher state, the atom is said to be excited and the process is termed as excitation. The atom goes to an excited state by absorption of a photon Once in the excited state, the atom cannot stay there indefinitely. There is non-zero probability that such an atom will lose energy and come to a state of lower energy by the emission of a photon. The processes of emission of photons when the transition of an atom from a higher to a lower state of energy is not caused by an external radiation, is called *Spontaneous Emission.* The probability (P_A) of spontaneous emission and the time (τ_e) that an atom spends in an excited state in the absence of external radiation are related (P_A=1 τ_e). Spontaneous emission from an assembly of atoms is of random character since photon emitted from different energies and momenta. Such photons constitute *Incoherent* light. The process of emission of photons when the transition in an atom

from a higher to a lower state of energy is caused by external radiation is called *Induced* or *Stimulated Emission* This process brings about *Coherence* in the emitted light

3.2. Components of a Laser

In order to produce a laser light three essential components are required.

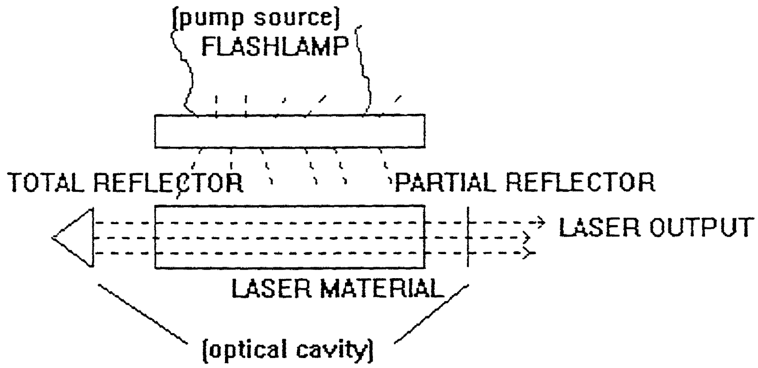

Fig. 3.1 Schematic diagram of laser

a) Laser Material. An assembly of atoms or molecules in gaseous, liquid or solid state in which conditions for light amplification (population inversion) are created.

b) Laser Resonator (Optical Cavity): A laser medium with significant population inversion is capable of amplifying light signal of appropriate frequency spectrum. In order to convert a light amplifier, into a light oscillator, a feedback mechanism is needed. This is provided by placing the active medium in a cavity, which usually consists of two ends mirrors and transparent sidewalls. The laser output usually comes out from one of the mirrors, which is partially transmitting

A Q-switch in the optical path is a method of providing laser pulses of extremely short time duration. A rotating prism like the total reflector in figure 3 was an early method of providing Q-switching. Only at the point of rotation when there is a clear optical path will light energy be allowed to pass. A normally opaque Electro-optical device (e.g., a pockels cell) is now often used for a Q-switching device. At the time of voltage application, the device becomes transparent, the light built up in the cavity by excited atoms can then reach the mirror so that the cavity Quality, Q. increases to a high level and emits a high peak power laser pulse of a few nanoseconds duration. When the

phases of different frequency modes of a laser are synchronized (locked together), these modes will interfere with each other and generate a beat effect. The result is a laser output with regularly spaced pulsation called "mode locking". Mode locked lasers usually produce trains of pulses with a duration of a few picoseconds to nanoseconds resulting in higher peak powers than the same laser operating in the Q-switched mode Pulsed lasers are often designed to produce repetitive pulses. The pulse repetition frequency, (PRF), as well as pulse width is extremely important in evaluating biological effects

3.2.1. Population Inversion

Amplification of light by an atomic system is possible if a non-thermo dynamical situation is created with more atoms put into a higher state as compared to a lower energy state Such a system is called a system with *Inverted Population* The population inversion is created in the active medium by feeding energy into it through an electric discharge or through such other means.

There are many types of amplifying medium that can be used in a laser through which light is amplified by population inversion and stipulated emission. In the normal state of laser medium, there are many more atoms in the lower state than the upper state. If the medium excited by appropriate method so that the number of atoms in the upper state N_u is greater than the number of atoms in the lower state N_l, then the light incident on the medium will be amplified by stimulated emission. This is the process of amplification

The process of making N_u greater than N_l at thermal equilibrium is *Population Inversion*. In order to invert the population of an atomic state. the atoms have to be excited by depositing energy in the medium by using a method to decrease an N_l atoms in the lower state and increase the number of N_u atoms in the upper state, this process is called *Pumping*.

3.2.2. Resonant Cavity

The final requirement for a laser is a resonant cavity that comprises a geometrical structure such as two parallel mirrors To achieve laser action, a resonant

cavity is required so that the light will make many passes through the active medium. Such an arrangement allows the light to travel a long distance in the medium.

For resonance to occur, an integral number of half wavelengths is needed between the mirrors. Laser action only occurs at discrete wavelengths satisfying the relationship,

$$q = (\lambda/2)d$$

for some integer of q, where d is mirror separation. λ is wavelength and q is an integer much greater than unity [9]

The terms cavity and resonator are used interchangeably in laser technology. All laser cavities share two characteristics that compliment each other·

I. They are basically linear devices with one relatively long optical axis.

II. The sides parallel to this axis are open rather than closed.

A simple resonator (shown in fig 3.2) is a device that consists of a pair of mirrors, which are, aligned plane parallel to each other One mirror is placed at each end of the laser media, with one mirror a total reflector while the other acts as partial reflector (or output coupler) This allows part of the of the generated laser beam to pass outside the cavity.

An output coupler allows, a portion of a laser light to leave the laser in the form of laser beam. The amount of light allowed to escape varies from one laser to another, from less than 1% for some helium neon lasers to more than 80% for some solid-state lasers.

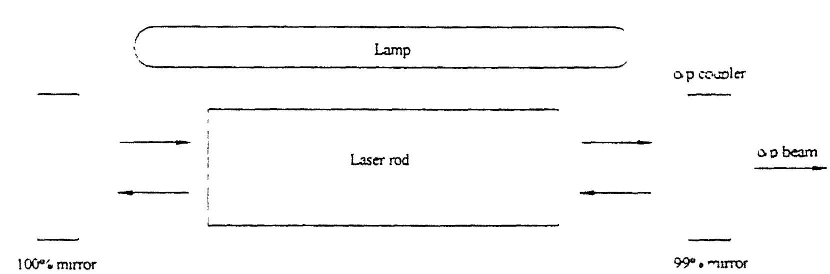

Fig3.2. Typical resonant cavity

The oscillation of laser light takes place in the cavity that is defined by the mirror at each end Because cavity length is several times longer than then the wavelength of the laser beam, it is possible to oscillate on several modes simultaneously. The simplest is the plane-parallel resonator called the Fabry-perot resonator Other configurations include the confocal resonator, hemiconfocal resonator, and the confocal resonator.

Laser resonators are described as stable and unstable. Stability refers to the condition where the threshold of stability is reached if a light ray is initially parallel to the cavity axis could oscillate between the mirrors forever without escaping from between them. Resonators that do not meet the stability criteria are called unstable resonators because light rays diverge away from the axis. But the design of unstable resonators collects higher volume of laser energy leading to higher overall efficiency than with the stable resonator. [10]

3.2.3. Pumping Mechanism

Electrons in the atoms of the lasing material normally reside in a steady-state lower energy state. When light energy from the pump source (flash lamp) is added to the atoms of the lasing material, the majority of the electrons are excited to a higher energy level -a phenomenon known as population inversion.

This is an unstable condition for these electrons. They will stay in this state for a short time and then decay back to their original energy state. This decay occurs in two ways: spontaneous decay (the electrons simply fall to their ground state while emitting randomly directed photons); and stimulated decay (the photons from spontaneous decaying electrons strike other excited electrons which causes them to fall to their ground state). This stimulated transition will release energy in the form of photons of light that travel in phase at the same wavelength and in the same direction as the incident photon. If the direction is parallel to the optical axis, the emitted photons travel back and forth in the optical cavity through the lasing material between the totally reflecting mirror and the partially reflecting mirror. The light energy is amplified in this manner until sufficient energy is built up for a burst of laser light to be transmitted through the partially reflecting mirror [8]

3.3. Types of Laser

Classification of lasers into families of devices is important to gain the specific knowledge individual lasers Several criteria could be used in categorization: [11]

Type of active medium, excitation method, output wavelength, output power, types of transitions etc First criterion is basic to operation the laser (in fact every laser is known by the name of its lasing material) Thus we have the following three broad categories of lasers:

Solid state lasers where lasing material can be a crystal like ruby or a semiconductor like GaAs.

Liquid lasers, which use liquid lasing material. Dye lasers are the most popular in this class.

Gas lasers where lasing material is in the form of a gas like Ar, N_2, and CO_2 or a vapour like Cd vapour.

3.3.1. Solid state lasers

The materials involved in producing of cascade of photons from this type are, as the name implies solids. The actual photon emitting atoms are generally from a small percentage of an element in a matrix of other compounds. For example, the ruby laser obtains its photons from the element chromium Cr, which is only a few percentage of the aluminum oxide matrix. The YAG laser radiation results from lasing of the neodymium atoms, which are a few percentage of the YAG (Yttrium Aluminum Garnet) matrix. [8, 10]

The emission wavelength of the laser is generally depends on the type of doped ions. The representative ions groups are transition metal ions and rare earth ions. Since crystals are nonconductive optical pumping is used for excitation.

The Nd:YAG laser and Nd:glass laser utilize transitions in Nd (Nd^{-3}) ions to generate lasing.[14] Nd:YAG lasers are four level lasers. For the YAG lasers, CW output of several tens of watts is available at 1.06 μm wavelength. These lasers may also be pumped using pulsed flash lamps and Q switching, generating pulses on the order of few nsec. at energies upto approx. 1 J This corresponds to peak powers of the order of 10^9 W. Much higher energies are possible from Nd·glass lasers because of they can have optical cavity of larger size so larger energy storage capability. An important

factor in design of this laser type is cooling system to keep the lasing material from deterioration, because only a small fraction of light energy is transferred to laser energy. Overall efficiency of a commercial Nd laser is 0.1 to 1%.

3.3.2. Liquid lasers

Several types of liquid have been used to create laser beams, but only one kind has been developed in a device of general usefulness. While a small number of inorganic liquids can function as lasers, the organic dye laser is the most popular. It consists of solid dye materials dissolved in an organic solvent such as alcohol to form solution. Organic dyes have energy levels so closely spaced that a number of these levels can produce a wide range of wavelength in the visible portion of the spectrum, 0.4-0.7 um. because of the wide range of wavelengths available in variety of dye solutions, dye lasers are described as tunable lasers. The output of the dye laser is typically of low power Dye lasers have a wide range of applications These lasers are used in applications involving chemical analysis and identification of atomic species [9]

3.3.3. Gas lasers

Among these three classes the gas lasers are the most common and they have the following distinct advantages over the solid state and liquid lasers. [11]

i. Spontaneous line widths are narrower in case of gases.
ii. Gases are optically more homogeneous.
iii. Larger volume of lasing material can be involved easily
iv. Heat produced by pump can be easily removed.

Gas lasers can be further classified into neutral atom, molecular and ion lasers. Excitation by electrical discharge is the main technique of producing population inversion in the gases The main mechanisms responsible for producing population inversion are the following:

i. Selective excitation of the upper level by plasma electrons. i.e.

$$X + e \rightarrow X^* + e \qquad \text{Or}$$

$$X + e \rightarrow (X^+)^* - e$$

ii. Selective excitation of the upper level by resonant collision with another atomic, ionic or molecular species

$$(A)^* + X \rightarrow A + (X)^* \qquad \text{Or}$$

$$(A)^* + X \rightarrow A - (X^+)^*$$

Where X can be a neutral atom or molecule.

The most useful and common lasers are:

- He-Ne lasers
- CO_2 lasers
- He-Cd lasers
- Ar-ion lasers
- N_2 laser
- Excimer laser

3.3.3.1. He-Ne laser

This is the neutral atom laser in which the Ne levels are populated by resonant collisions with excited He atoms The laser can lase at 33912.2 nm, 1152.3 nm, and 632.8 nm, the last being the most popular.

3.3.3.2. Excimer laser

Excimer lasers use an interesting class of molecules as lasing material whose ground state is repulsive while the potential energy curve for the excited state has a minimum, as shown in the figure. Consequently, such a molecule does not exist in the ground state but a large population can be produced in the excited state, which can lead to laser action. It is quite obvious that such a system have quite a high gain because ground state is always with zero population. These lasers generate short pulses of high power in the ultraviolet range. The excimer molecules are produced by electron impact and bimolecular collision processes.

3.4. Q Switching

Like any oscillator, a laser cavity has a quality factor Q that measures the loss or gain of the cavity. This factor is defined (Thyagarajan and Ghatak, 1981) as

$$Q = \frac{\text{energy stored per pass}}{\text{energy dissipated per pass}}$$

Normally, the Q factor of a laser cavity is constant, but modulating the Q factor raises interesting possibilities. If the Q factor is artificially low, say by putting an energy dissipative optical element into the cavity, energy will gradually accumulate in the laser medium because the Q factor is too low for laser oscillation to occur and dissipate the energy If the loss is removed suddenly, the result is a large population inversion in a high Q cavity, producing a high power burst of light, a few nanoseconds to several hundred nanoseconds long, in which the energy is emitted This rapid change in cavity Q is called Q switching [9, 11]

There are three basic variations on Q switching One is use of a rotating mirror or prism as the rear cavity mirror. Another is insertion of modulator into the cavity. The third is insertion of nonlinear energy dissipative element into the cavity that becomes transparent once intra cavity power is exceed a certain level. The first two techniques are called active Q switching and the third is known as passive Q switching

Q switching of pulse laser cannot increase pulse energy, but it can squeeze much of that energy into a pulse and achieve peak powers in the megawatt range.

4. Ionization of atmospheric air

4.1. Air Ionization

Air constitutes of many gases The composition of the air is given in the Appendix A One can consider the composition of air to have mainly two gases, i e N_2 (nitrogen) and O_2 (oxygen) Roughly 80% of air is the nitrogen and 20% oxygen O_2 is an electronegative gas hence it has a property of absorbing electrons to produce negative ions. When the high power laser beam of intensity (I W cm^2), interacts with air, electrons can be generated through two main mechanisms·

1) Multi-photon ionization (MPI)

2) Cascade ionization

The relative importance of these two processes is expected to change dramatically with pressure. MPI is expected to become dominant when low pressures and short duration laser beams are used. This is because inverse bremsstrahlung (IB) absorption requires a three-body interaction, namely photon, free electron and atom Depending upon the electron removal processes, diffusion, recombination etc., strong pressure dependence is expected; here threshold power density (I_{th}) is inversely proportional to pressure. Thus, when electron-atom collision frequency ν_m, which depends upon pressure, becomes higher than the laser frequency, IB absorption becomes efficient. A very weak pressure on the laser intensity required to cause ionization characterizes the transition to MPI. Mathematically laser intensity can be derived proportional to $p^{-1/n}$. Where p is the pressure in Torr and n is the number of photons simultaneously absorbed to ionize an atom. [27, 28]

In the second process, the cascade ionization process, electrons gain energy from the laser field through electron impact ionization with the neutral atoms or molecules The electrons can readily ionize air when their energy exceeds E_I, ionization potential of the gas. At sufficiently high fields, ionizing collisions in cascade are caused to occur with the electron density increasing exponentially with the time. Cascade breakdown is

the dominant mechanism at long wavelengths of ($\lambda \geq 1\mu m$). As the wavelength is shortened below 1μm, multi-photon ionization is expected to play an increasingly important role in the breakdown process. [23, 24, 26]

The optical breakdown field is a function of the spot diameter of the focused point and the breakdown field increases as the spot diameter decreases This occurs because as diameter decreases the power density increases. The relation between electric field at focused point and the power density at the focused point are related as.

$$E^2 = 8\pi \frac{I}{c}$$

Where E is the electric field in V/cm , I is the power density in W/cm^2 and the 'c' is the speed of the light in cm/s. [7]

4.2. Multi-photon Ionization

Multi-photon ionization (MPI) involves the simultaneous absorption by an atom or molecule of a sufficient number of photons to cause its ionization (or to eject an electron from the valence band to conduction band). MPI is described by the reaction

$$M + nhv \rightarrow M^- + e^-$$

Where 'M' is atom or molecule and hv is the photon energy. If E_I is the ionization potential, the number of photons n must exceed the integer part of $\left(\frac{E_I}{hv} + 1\right)$. The ionization rate in a laser beam of power density I is proportional to I^n and the electron density, for a constant intensity pulse, increases linearly with time. Number of photons required to ionize oxygen and nitrogen for different kinds of lasers is given in table 4.1.

The number of electrons liberated by the process of multi-photon ionization, in a volume dV, during a time dt, can be written as [24, 25, 28]

Table 4.1. Number of Photons required to ionize N_2 and O_2 for different types of lasers

Types of laser (Wavelength, pulse width, Pulse energy, type of laser)	Photon energy in (eV)	Number of Photons require for Ionization	
		Nitrogen	Oxygen
0.248 µm, 22 fs, 750 mJ (Excimer Laser)	5.00	4	3
0.526 µm, 500 fs, 120 mJ, (Nd Glass Laser)	2.36	7	6
0.633 µm, CW, 5 mW (He-Ne Laser)	1.96	9	7
1.06 µm, 300 ns, 20 J, (Nd: YAG Laser)	1.17	14	11
10.6 µm, 50 ns, 50 J, (CO2 Laser)	0.12	130	101

$$dN_e = NAP^n dVdt \qquad \ldots\ldots\ldots \qquad (4.1)$$

Where N is the density of neutral atoms in the gas and roughly the value of N is $4.56 \times 10^{16}p$, where p is the pressure of the gas in Torr.

(4.1) is valid with the assumption that the multi-photon ionization probability for an atom can be expressed in the form (AP^n) where A, n are the constant for the particular gas and P (x,y,z,t) is the 'laser pulse profile' defining its spatio-temporal characteristics. If the relative distribution does not change with the time, then P can be written as

$$P=S(x,y,z)*I(t)$$

If we assume that the distribution S(x,y,z) of the laser radiation is gaussian, then (4.1) can be written as

$$dN_e = I^k(t)\frac{NA}{k^{3/2}}\Delta V dt$$

this is the number of electrons liberated in the focal volume ΔV during time dt. The rate of change of electron density ($n_e=N_e/\Delta V$) in the focal region due to multi-photon ionization (MPI) is then given by the relation

$$\left(\frac{dn_e}{dt}\right)_{MI} = \frac{NA}{k^{3/2}}I^k(t) \qquad \ldots\ldots\ldots\ldots \qquad (4.2)$$

4.3. Cascade Ionization

In a powerful laser pulse the electrons generated by the MPI process will subsequently be accelerated by the field induced by laser and undergo ionizing collisions with gas atoms to form a cascade. In term of total ionization collision frequency ν, the growth of the electron density by this mechanism can be written as

$$\left(\frac{dn_e}{dt}\right)_C = \nu n_e \qquad \ldots\ldots\ldots\ldots \qquad (4.3)$$

for moderate laser power this ionization collision frequency is linear function of the laser intensity I(t),

$$\frac{\nu}{N} = \left\{\frac{377q}{\omega^2}\left(\frac{\nu_m}{N}\right)^2\right\}I(t) \qquad \ldots\ldots\ldots\ldots \qquad (4.4)$$

Where q is a constant for a particular gas and the typical value of the q is of the order of 10^{21} $cm^{-1}s^{-1}v^{-2}$, ω is the angular frequency of the laser radiation and ν_m is electron atom collision frequency in (s^{-1}) for momentum transfer, which is assumed to be independent of electron energy. [29]

Combining (4.2) and (4.4) gives the total growth rate of electron density in the focal region at any time t during the laser pulse as

$$\frac{dn_e}{dt} = n_e N \left\{ \frac{377q}{\omega^2} \left(\frac{\nu_m}{N} \right)^2 \right\} I(t) - \frac{NA}{n^{3/2}} I^n(t) \qquad \ldots\ldots \quad (4.5)$$

where A is the multi-photon ionization coefficient and can be calculated by the equation given below

$$A = \frac{\sigma^n}{\left[\nu^{n-1} (n-1)!(h\nu)^n \right]} \qquad \ldots\ldots \quad (4.6)$$

Ideally we can assume laser pulse of triangular shape of width 2τ and peak energy E_0.

$$I(t) = \frac{E_0}{\tau} t \qquad 0 \le t \le \tau$$

$$I(t) = \frac{E_0}{\tau}(2\tau - t) \qquad \tau \le t \le 2\tau$$

(4.5) describes the rate of growth of electron density in the focal region due to the combined effect of MPI and cascade ionization processes in the laser pulse in the absence of any electron removal process.[29]

With the help of the equation of growth of electrons, including the effect of both MPI and cascade ionization, theoretical calculations of laser-induced breakdown thresholds were carried out as a function of pressure and pulse length for different wavelengths. The breakdown threshold intensity I_{th} for N_2 and O_2 gases is calculated for 1.06 μm, 0.633 μm and 0.248 μm wavelengths. For this calculation of threshold intensity required to cause ionization due to simultaneous effect of both MPI and cascade ionization (CI) mechanisms over the whole pressure range, the degree of fractional ionization δ of gas atoms in the focal volume is assumed to be ~ 0.1%. [20, 21, 26]

The calculated values of I_{th} for various pressures of N_2 and O2are plotted in the fig. 4.1 for λ=1.06 μm laser radiation. The curve for N_2 is plotted using the values n=13, ν_m=(5 49x10^9) p·s^{-1}Torr. For the estimation of I_{th} for oxygen the values are n = 11, ν_m= (4.4x10^9) p s^{-1}Torr were considered. The value of q is taken to be q=4.29x10^{20} cm^{-1}s^{-1}V^{-2} for both nitrogen and oxygen. [24, 28, 29]

Fig. 4.2 shows threshold intensity of laser radiation at λ=0.633 μm. The theoretically calculated curve of I_{th} for N_2, was derived using the values of the parameters ν_m=(5.49x10^9) p s^{-1}Torr, q=4.29x10^{-20} cm^{-} s^{-1}V^{-2} and n =7. For oxygen

ν_m=4.4x10^9)p s^{-1}Torr, q=4.29x10^{20} cm^{-1}s^{-1}V^{-2} and n =6. [24, 28, 29]

For λ=0.248 μm, the plots between I_{th} and pressure are shown in the fig. 4.3. The values used to plot the graph for N_2 are ν_m = (5.49x10^9) p s^{-1}Torr, q = 4.29x10^{20} cm^{-1}s^{-1}V^{-2} and n=4. The plot for O_2 plotted with the values ν_m = (4.4x10^9) p s^{-1}Torr, q = 4.29x10^{20} cm^{-1}s^{-1}V^{-2} and n=3.The value of multi-photon absorption coefficient A is calculated by (4.6). [24, 28, 29]

From these figures, it shows that for smaller wavelengths threshold intensity of oxygen is less compared to nitrogen. this is due to the fact that the ionization potential E_I of oxygen is less as compared to nitrogen. For wavelengths $\lambda \leq 1$ μm, MPI dominates, because smaller number of photons is able to ionize the atom. Hence the I_{th} required for ionization of O_2 atom is smaller than N_2. at wavelength in UV range, the effect of pressure is negligible on threshold intensity of laser as shown in fig. 4.3.

From this analysis for Nitrogen and Oxygen atoms, it can be estimated that the threshold laser intensity required to ionize the air is of the order of 10^{12} W/cm^2.

Such high power intensity can be obtained from pulse laser only. For obtaining intensity of the order of 10^{12} W/cm^2, we need the pulse width of laser pulse in the range of 10^{-12} sec.

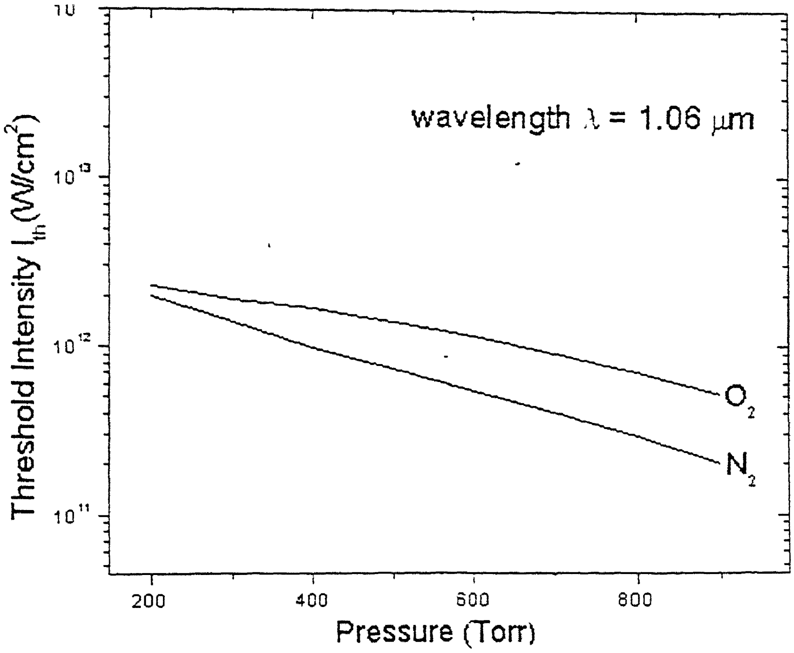

Fig. 4.1. Plot between Pressure and Threshold Intensity of laser for $\lambda = 1.06\ \mu m$

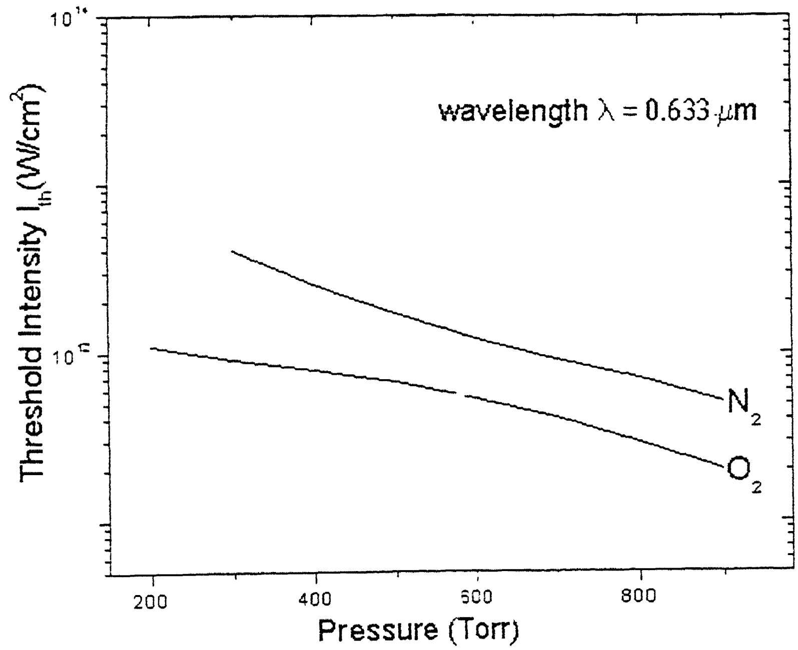

Fig. 4.2. Plot between Pressure and Threshold Intensity of laser for $\lambda = 0\ 633\ \mu m$

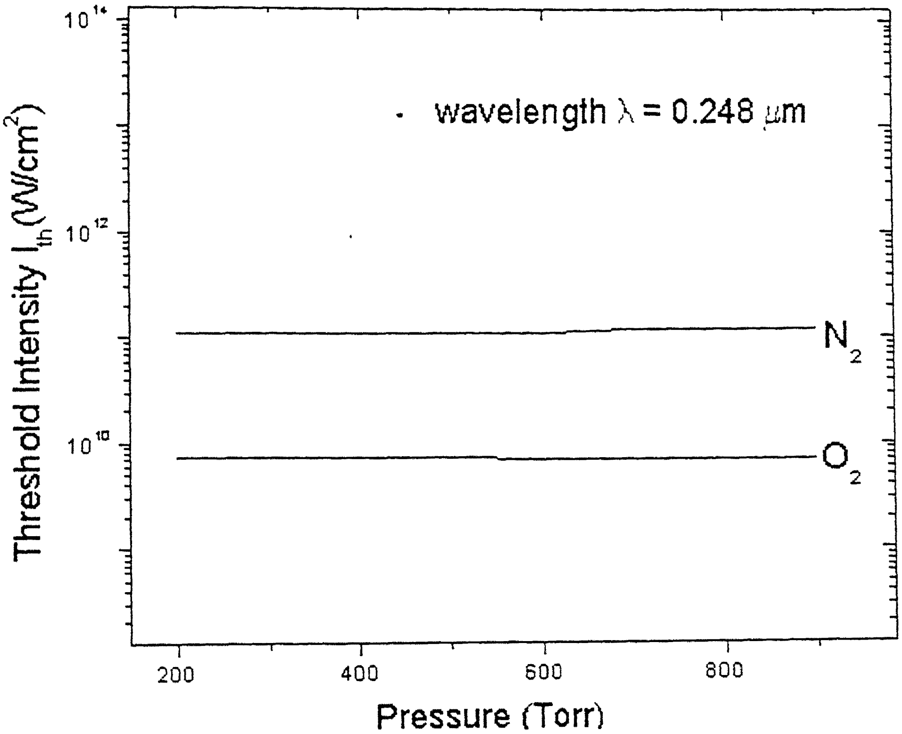

Fig. 4.3. Plot between Pressure and Threshold Intensity of laser for $\lambda = 1.06\ \mu m$

5.1. Experimental Set-Up

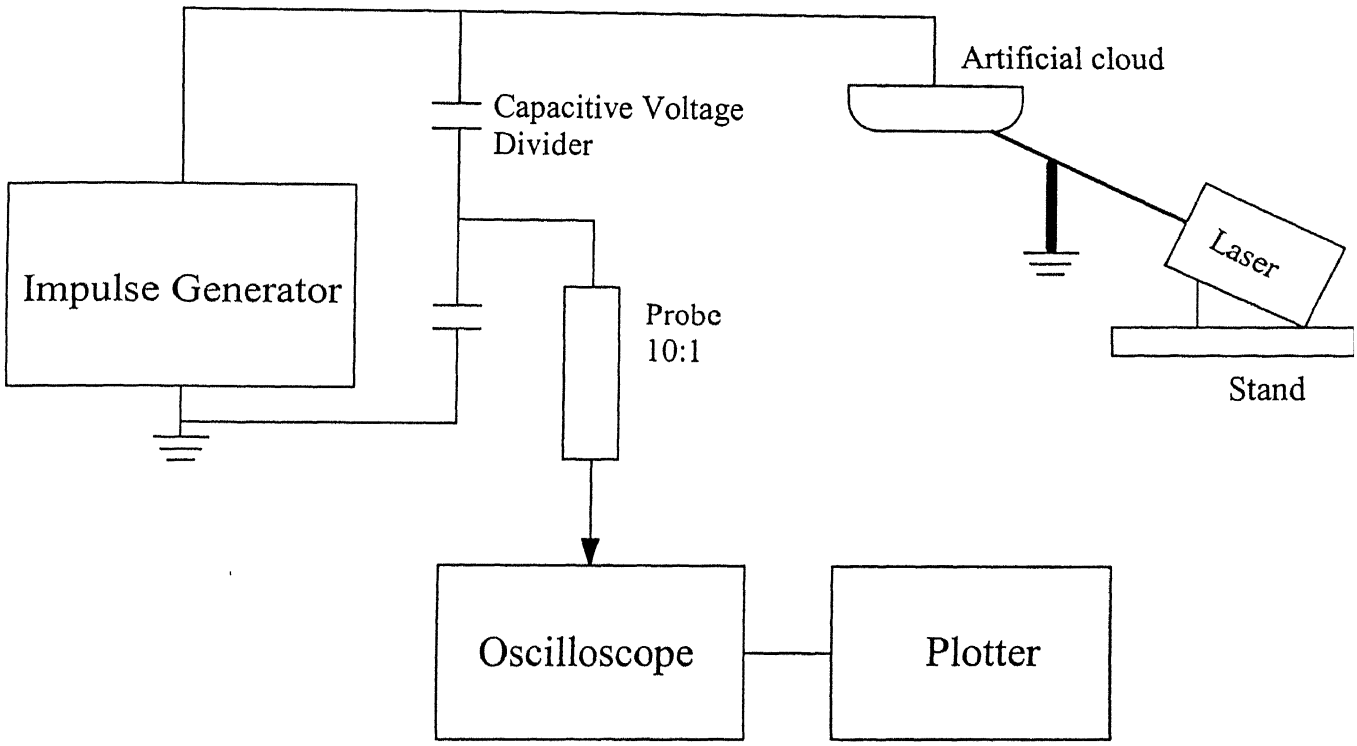

Fig. 5.1. Schematic diagram for experimental set up

5.1.1. Impulse Generator

A four stage 500 kV impulse generator was used for this experimental work. The specifications are given in the table 5.1. The output of the impulse generator was connected to a capacitive voltage divider having ratio of 750:1. The impulse generator could be triggered with the help of a trigatron circuit, which produce pulse of 10 kV at an interval of 5-30 seconds. The duration between successive impulses could be set automatically or they could be provided manually also. Impulse generator front and side views with capacitive voltage divider are shown in the photographs in fig. 5.2 and 6.3 respectively.

Table5.1.: Specifications of Impulse generator

Specifications	**Value**
Max. Charging voltage	500 kV
Max. No load output voltage	450 kV
Rated energy	4.4 kJ
Number of stages	4
Input voltage	440 V, 3ϕ
Capacitor per stage voltage	140 nF, 125 kV
Wave shape of li	1.2/50 μS
Manufacture	TUR Germany

5.1.1.1. Design and operation of impulse generator

An impulse generator requires a dc power supply for charging the input capacitor C_1 the supply consist of a step up transformer and a rectifier, non inductive wire wound resistors are used. Resistors are placed as convenience of replace and exchange. The type of capacitors used mainly decides the lay out of the impulse generator. Generator consist of oil impregnated, paper dielectric capacitors arranged one above the other with center tapping and ohmic resistors connected in parallel. The coupling sphere gaps are arranged one above the other on horizontal arms and the settings of the gaps is adjusted by a remotely controlled motor in conjunction with an indicator

The charging voltage is applied to the system. The stage capacitor charged through the charging resistors. When fully charged, either the lowest gap is allowed to breakdown from over voltage or it is triggered by an external source (if the gap spacing is set greater than the charging voltage breakdown spacing). This effectively puts the bottom two capacitors in series, overvoltaging the next gap up, which then puts the bottom three capacitors in series, which overvoltage the next gap, and so forth. This process is referred to as *erecting*. A common specification is the erecting capacitance of the bank, equal to the stage capacitance divided by the number of stages. [13]

Impulse generator is operated in conjunction with CRO for measurement and analysis of waves. As the impulse are of shorter duration. so it is necessary that the operation of generator and the oscillograph should be synchronize accurately. The time sweep circuit of the oscillograph is initiated at time slightly before the impulse wave reaches to the deflecting plates.

Trigatron is a device used for producing initiating electrons for breakdown of the spark gap. The trigatron consist of a three-electrode gap. The main electrode, which are high voltage and ground electrode are sphere or semi sphere electrode configurations A small hole is drilled into the earthed electrode into which a metal rod is projected The annular gap between the rod and the surrounding sphere is typically about 1 mm The metal rod or trigger electrode forms the third electrode. It is connected to earthed electrode through a high resistance. A tripping pulse is given between these two electrodes. A glass tube is fitted across the rod and is surrounded by a metal foil connected to the potential of the main electrode. The function of this tube is to promote corona surface discharge around the rod as this causes photo ionization of the pilot gap. if a tripping pulse is applied to the rod. Due to this photo ionization enough primary electrons are available in the annular gap, which breaks down without appreciable time delay. The glass tube also fill the annular gap so that rod as well as tube with its face is flush with the outside surface of the sphere. Thus a surface discharge is caused by a tripping pulse. Trigatron requires a pulse of 5 kV of the both polarity. [2]

5.1.2. Load unit

The load unit consists of oil impregnated. paper dielectric capacitors arranged one above the other with center tapping and ohmic resistors connected thereto in parallel Load unit also work as capacitive voltage divider of ratio 750:1 The rating of the capacitor is 1.5 nF, 600 kV.

5.1.3. DC Generator

In a sheet steel tank displaceable on rollers and filled with transformer oil, DC generator is used to produce a high dc voltage to earth which serves as charging voltage for the generator. HT transformer, HT rectifier and HT measuring resistor are fixed connected to the cover. Other components of impulse generator are discharge switch. control cubicle, control panel.

5.2. Oscilloscope

A digital storage oscilloscope of KIKUSUI (COR 5502 U) 100 Mhz is used to measure the magnitude of impulse voltage and propagation time Output from the capacitive voltage divider is fed to oscilloscope through a probe of ratio 10.1. Therefore the total reduction factor between the actual applied voltage and to test object voltage to oscilloscope is 7500.1 Thus voltage reading of oscilloscope is multiplied by a factor of 7.5 directly gave the value in kV. A digital plotter is connected to oscilloscope to obtain the wave shape plot through RS 232 serial interface. Control panel, oscilloscope and plotter are shown by photograph in fig. 5.3.

5.3. Laser

For our experimental work we used He-Ne laser It is small in size The light emitting from this laser is monochromatic in nature and of wavelength 632.8 nm. It is CW (continuous beam) laser. It can concentrate large amount of light into a very narrow beam. The output power of this laser is 5 mW. The intensity (power divided by area) is approximately 0.65 W/cm^2. The specifications of the He-Ne laser are given in the table 5.2.

Table5.2.. Specifications of He-Ne laser

Specifications	**Value**
Wavelength	632.8 nm
Peak power	5 mW
Power at turn on	>80%
Beam diameter	0.83 ± 0.02 mm
Beam divergence	1.0 mrad
Polarization	Linear
Input Voltage	$220 \pm 10\%$ V
Power Rating	0.5 A
Operating Temperature	0 to 60^0 C

5.4. Electrode Preparation

In the laboratory we prepared an artificial cloud. We used an aluminum plate, which is hard fabricated into a shape of a large inverted bowl, approximately 75 cm. in diameter. The cloud was suspended from the ceiling with the help of a string of five units of toughened glass insulators each having 20 kV withstanding voltage capacity. HV impulse generator was connected to this inverted bowl, which simulated a large cloud for our experimental investigations. For ground electrodes we used two types of electrodes

a) Rod Total length = 10.5 cm, Diameter = 0.08 cm.

b) Needle Total length=10 0 cm, Taper length=4 cm, Taper angle=6^0,Diameter=0 12 cm.

To hold the electrodes a stand of Perspex ebonite is used which also have arrangement to change the gap between the electrode and the cloud. Before starting the experiments, the electrodes were first cleaned with Acetone and then dried with the soft cloth.

5.5. Atmospheric Conditions

Atmospheric conditions during experiments are:

Temperature range : 20-30 °C

Pressure range . 760-770 mm Hg

Humidity 60-70%

6. Experimental Investigations

6.1. Introduction

Experiments were performed to study the effect of laser on the insulating properties of atmospheric air. A Schematic diagram of experimental set-up is shown in fig 5.1.

A cloud was simulated by a aluminum electrode of a big size connected to the output of impulse generator as shown in the fig.6.2 and 6.3. Measurement of output voltage of impulse generator was accomplished by CRO connected through capacitive voltage divider. Impulse generator and electrode set-up were locked behind the safety fence. Safety door was locked and whole set-up is controlled through control panel and control cubicle from outside Control panel contains various meters for reading of voltage (input & output), current and spark gap distance. It also has mechanism for controlling voltage magnitudes and its polarity and spark gap distance. Triggering pulse can be applied externally from control panel or it can also be set automatically for an unknown regular interval from control cubicle. Control cubicle was also having an option for counting number of pulses, generated repetitively for triggering with the help of a counter.

6.2. Experimental Procedure

The artificial cloud electrode fabricated at our laboratory was hanged from the ceiling with the help of an insulator string of five units. The high voltage was applied to the big electrode of bowl shape. Hemispherical rod and needle shaped electrodes were chosen as ground electrode. Laser was focused in such a manner that bridged the high voltage electrode with the ground electrode. Desired polarity of lightning impulse voltage was chosen. The charging voltage level of the impulse generator is raised gradually not exceed the limit of 1 kV/sec from the control panel.

Gap distance between the cloud and ground electrode was set keeping in mind the limitations of our impulse generator. Stage spark gap configuration of sphere-sphere has breakdown strength around 20 kV/cm. For Test objects of needle or rod-cloud, the

breakdown strength of the gap is around 7 kV/cm for positive and around 15 kV/cm for negative polarity voltages respectively

For needle-cloud electrodes having gap distance of 10 cm with positive polarity the estimation of breakdown voltage is as follows. The approximate breakdown voltage for this case is expected to be 70 kV. Hence voltage to be generated per stage by the four-stage impulse generator is 70/4 = 17.5 kV. Therefore the stage spark gap distance should be set at 17 5/20 = 8 75 mm It is preferable to set stage spark gap distance to some what lower value of 9 mm and voltage level is increased slowly until first breakdown takes place.

6.2.1. Determination of 50% breakdown voltages (U_{b50})

While increasing the output voltage first breakdown takes place, the magnitude of the applied impulse voltage was kept constant and the pulses are applied at regular intervals of 30 seconds Total 10 shots of a particular voltage level were applied and the number of shots for which breakdown occurred was counted. The percentage breakdown voltage for a particular gap is obtained by dividing the number of shots at which breakdown occurred with the total number of shots applied. Then the voltage is varied and the above procedure is repeated till 50% breakdown voltage U_{b50} is obtained i.e. breakdown take place for 5 pulses out of 10 pulses.

6.2.2. Propagation of Breakdown Channel

With lightning impulses, it is possible that breakdown may not occur even when the peak voltage magnitude exceed the lowest breakdown voltage. unless the presence of sufficient number of initiatory electrons is ensured. The delay in the beginning of the discharge process is called *Statistical time lag* (t_s) The statistical time lag depends upon the area of the electrode, the gap distance and magnitude of radiation producing primary electrons.

Once the discharge process begins, it requires a certain finite time called *Propagation time* (t_p) to reach the opposite side electrode. The total propagation time (t_p) in a gap depends upon the individual type of PD and their extent in the gap just before the breakdown.

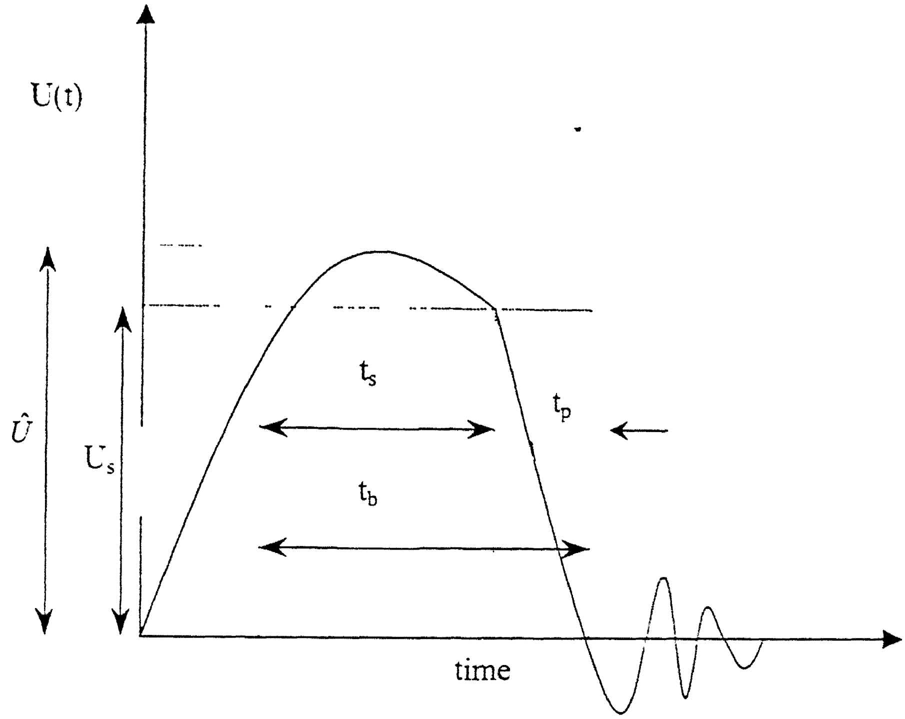

Fig. 6.1: Time required for the formation of breakdown with the impulse voltage

Total time required for formation of breakdown t_b is

$$t_b = t_s + t_p$$

t_s = Statistical time lag

t_p = Propagation time

U_s = Lowest breakdown voltage

$\hat{U}$ = Peak magnitude applied

The leader propagation time with impulse voltages can be considered to be from the instant the applied voltage begins to collapse to the instant when it reaches to zero. The Propagation time could be measured accurately with the help of storage oscilloscope. Propagation velocity of the breakdown channel is estimated assuming that the leader takes the path through the shortest gap distance between electrodes. [13]

$$\text{Propagation velocity} = \frac{\text{Gap distance}}{\text{Propagation time}}$$

Propagation velocity is reported to be a few tens of cm/μs and for streamer discharge 100 cm/μs. Leader propagation velocity depends upon the electrode configuration and shape of the applied impulse voltage.

6.3. Results and Discussion

The experiments were performed keeping the gap distance 16 cm fixed between cloud and ground electrode. First the investigations were made with cloud-rod electrode configuration The laser was focused in between the high tension and ground electrode Then a series of 10 pulses applied with 30 seconds time interval between two consecutive pulses. First series of 10 pulses were applied to electrode set-up without focusing laser and the breakdown voltage U_b, statistical time lag t_s, propagation time t_p and propagation velocity were measured with the help of oscilloscope for each pulse The values are shown in Table6 1. Then another 10 pulses were applied under the presence of focused laser. The values are shown in the Table 6.2. No significant variation in U_{b50} could be measured. It was expected that the probability of breakdown would increase under the presence of the laser beam but no changes could be measured. The propagation velocity of the leader discharge which depends upon the number of free electrons present, was also measured there was no significant change observed in propagation velocity in the two cases

Same experiments were repeated with cloud-needle electrode configuration and also for negative polarity of lightning impulse voltage. Experimental results are shown in the Table 6.3 and Table 6.4. Experiments were performed with cloud-rod electrode configuration by changing the polarity of impulse voltage. the results are shown in the Table 6.5 and Table 6.6

Theoretical study of the ionization of air induced by laser radiations has been made in Chapter 4. In atmospheric air mainly two mechanisms are responsible for air ionization. The first one is multi-photon ionization (MPI) and the second one is cascade ionization. Minimum intensity of the laser required to ionize the air is of the order of 10^{12} W/cm^2 Such high laser power density is not possible to be obtained from CW laser. It can only be achieved with the help of pulsed laser. In pulsed laser the energy of the pulse

is small but the peak power of the pulse is much higher and it depends upon the pulse width.

The ionization of air also depends upon the wavelength of the radiation and the area of the focused point The laser having wavelength in UV range can ionize N_2 and O_2 atoms with less number of photons because of the fact that the photon energy of the photons emitting from UV laser radiations is much larger than photon energy of infra red lasers and lasers having wavelength in visible region

The He-Ne laser used in those experiments was having wavelength of 638.3 μs and the nature of the beam is continuous beam (CW). The peak power of He-Ne laser is 5 mW and the approximate power density is 0 67 W/cm^2. Based on theoretical studies, this power density is insufficient to be able to ionize the air. Hence it appears to be the reason for having measured no significant effect on the breakdown strength on the application of He-Ne continuous beam laser.

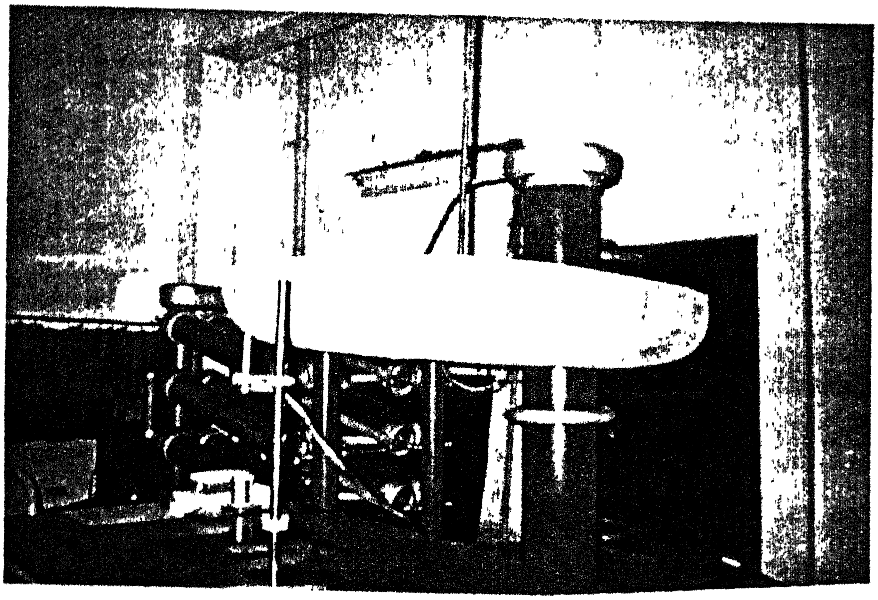

Fig. 6.2. Cloud-Rod electrode Configuration

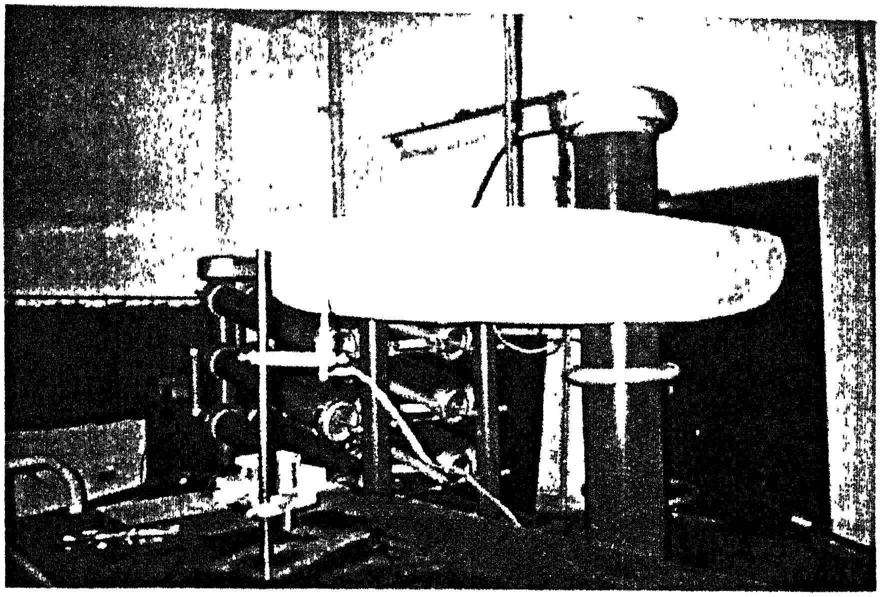

Fig. 6.3. Cloud-Rod electrode Configuration

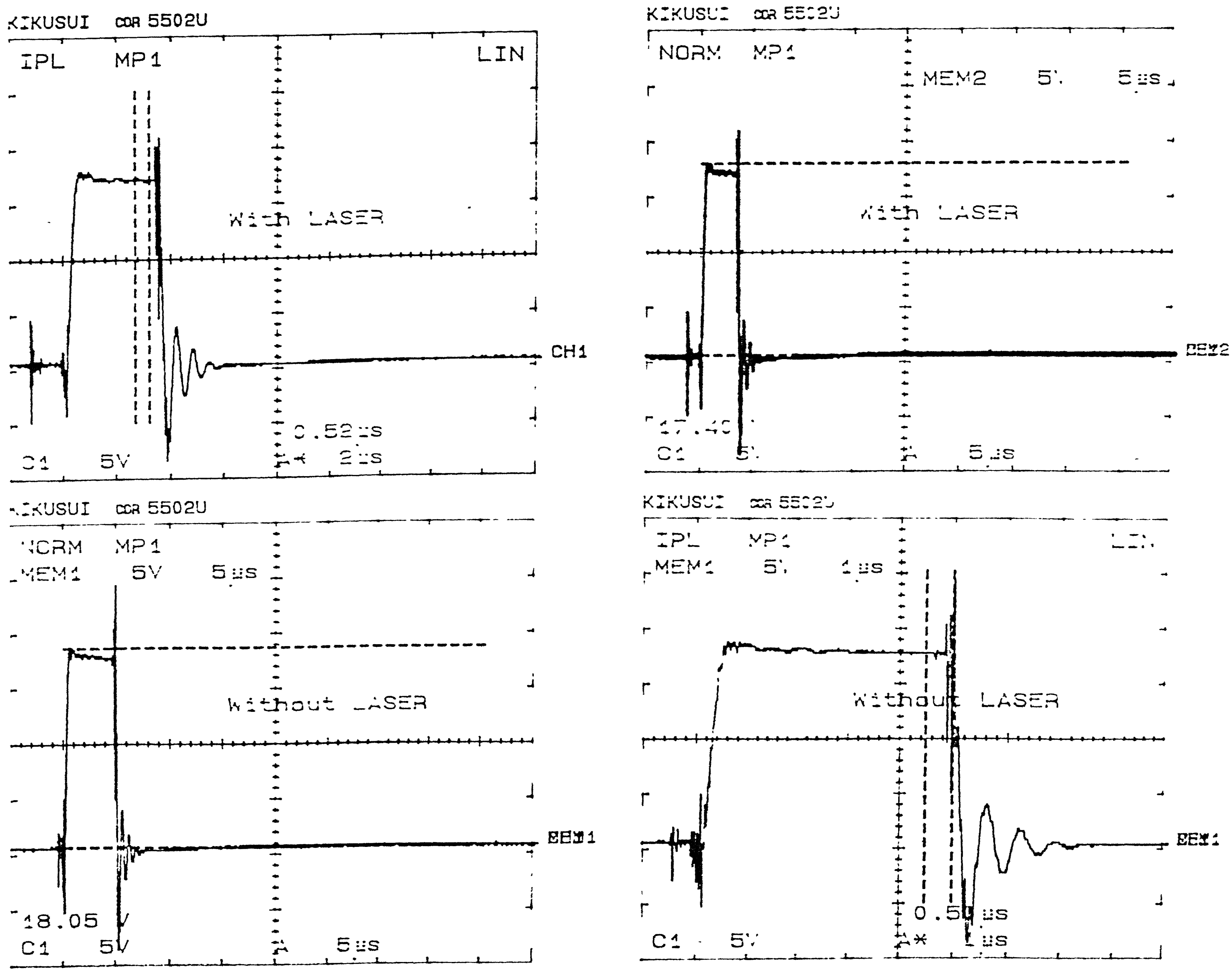

Fig.6.4. Oscilloscope showing U_b breakdown voltage and propagation time for cloud-needle electrode, with and without laser

Table 6.1: Cloud-Needle electrode (without Laser), 16 cm. gap with positive polarity

No of pulses	Breakdown voltage U_b(kV)	Statistical time lag t_s(µs)	Propagation time t_d(µs)	Propagation velocity (cm/µs)
1	NO BREAKDOWN			
2	129 50	2.48	0.50	32.00
3	129 50	2.70	0.50	32.00
4	129 50	3.16	0.50	32.00
5	NO BREAKDOWN			
6	NO BREAKDOWN			
7	NO BREAKDOWN			
8	129 50	3.96	0.48	33 33
9	129 50	2.76	0.48	33.33
10	NO BREAKDOWN			

Table 6.2: Cloud-Needle (with Laser), 16 cm gap distance with positive polarity

No of pulses	Breakdown voltage U_b(kV)	Statistical time lag t_s(µs)	Propagation time t_d(µs)	Propagation velocity (cm/µs)
1	129 50	3.10	0.54	29.63
2	129 50	3.26	0.52	30.77
3	129 50	2.94	0.46	34.78
4	NO BREAKDOWN			
5	NO BREAKDOWN			
6	NO BREAKDOWN			
7	NO BREAKDOWN			
8	129 50	2.84	0.48	33.33
9	129 50	3.04	0.52	30 77
10	NO BREAKDOWN			

Table 6.3: Cloud-Rod (without Laser), 16 cm gap with positive polarity

No of pulses	Breakdown voltage U_b(kV)	Statistical time lag t_s(µs)	Propagation time t_p(µs)	Propagation velocity (cm/µs)
1	125 63	3.06	0.50	32.00
2	NO BREAKDOWN			
3	NO BREAKDOWN			
4	125 63	3.04	0.50	32.00
5	NO BREAKDOWN			
6	125 63	3 62	0.48	33.33
7	NO BREAKDOWN			
8	NO BREAKDOWN			
9	125 63	2.98	0.48	33.33
10	125 63	4.20	0.50	32.00

Table 6.4: Cloud-Rod (with Laser) 16 cm gap with positive polarity

o of pulses	Breakdown voltage U_b(kV)	Statistical time lag t_s(µs)	Propagation time t_p(µs)	Propagation velocity (cm/µs)
1	125 63	2.98	0.50	32.00
2	125 63	3.86	0.52	30.77
3	125 63	3.42	0 48	33.33
4	NO BREAKDOWN			
5	NO BREAKDOWN			
6	125 63	2.95	0 50	32.00
7	NO BREAKDOWN			
8	125 63	3 38	0.48	33.33
9	NO BREAKDOWN			
10	NO BREAKDOWN			

Table 6.5: Cloud-Rod (without Laser), 16 cm gap with negative polarity

No of pulses	Breakdown voltage U_b(kV)	Statistical time lag t_s(μs)	Propagation time t_p(μs)	Propagation velocity (cm/μs)
1	229 50	5.95	0 58	27 59
2	229 50	4 86	0 62	25 81
3	229 50	5.42	0 56	28.57
4	NO BREAKDOWN			
5	NO BREAKDOWN			
6	229 50	5 95	0 60	26 67
7	NO BREAKDOWN			
8	229 50	2.38	0 58	27 59
9	NO BREAKDOWN			
10	NO BREAKDOWN			

Table 6.6: Cloud-Rod (with Laser), 16 cm gap with negative polarity

No. of pulses	Breakdown voltage U_b(kV)	Statistical time lag t_s(μs)	Propagation time t_p(μs)	Propagation velocity (cm/μs)
1	229 50	5.92	0 56	28 57
2	NO BREAKDOWN			
3	NO BREAKDOWN			
4	NO BREAKDOWN			
5	229 50	4 98	0.56	28 57
6	229 50	5.95	0.58	27 59
7	NO BREAKDOWN			
8	229 50	3 38	0 58	27 59
9	NO BREAKDOWN			
10	229 50	6 34	0 62	25 81

7. Conclusion and scope for future work

7.1. Conclusions

1. Experiments were performed in this work to observe the effect of laser on the breakdown strength of air First the breakdown voltage was measured without focusing laser and then breakdown was measured with the focused laser for the same gap distance. No significant effects were observed on the breakdown strength of air with laser.

2. Theoretical study of the ionization in laser beam reveals the laser intensity should be at least of the order of 10^{12} W/cm^2 to be able to ionize the air. It may result into influencing in the breakdown strength of air.

3. Pulse lasers can achieve such high laser intensities of the order of 10^{12} W/cm^2. In the pulse laser energy per pulse is very small of the order of mJ but the peak power, which can be achieved, is of the order MW. This peak power also depends upon the pulse width.

4. The power of laser used in experiments performed at H.V. laboratory is compared with the laser power that other authors used. A comparison is done in the table.7.1.

Table7.1. A comparison of laser output power between laser used in laboratory to other author's used in their experiments

Types of Laser (wavelength, pulse energy, pulse width and type of laser)	Maximum Output Power in Watts (Max. Power =pulse energy/ pulse width)
0 248 μm, 750 mJ, 22 ns, Excimer (KrF) Laser	$34x10^6$
10.06 μm, 50 J, 50 ns, CO_2 Laser	$1x10^9$
0.633 μm, CW, He-Ne Laser	$5x10^{-3}$

5. Experiments were performed by bridging the two electrodes with laser beams while literature study shows the experiments with focusing laser.

7.2. Scope for Future Work

- In these experiments performed in the laboratory, the laser used was of very low intensity that could not ionize the air. Sufficient number of free electrons is not present to increase the probability of breakdown of lightning impulses. It would be worth performing the experiments with higher intensity lasers.

- In the study of ionization of air we considered air as 80% nitrogen and 20% oxygen, but many gases are present in air. Study can also be performed by considering other gases.

- Calculation of threshold intensity for different wavelength lasers is done on theoretical basis. It can be compared with the experimental results by performing the experiments.

- The ionization of air induced by laser radiation is reduces as the time goes, this effect can be visualize by keeping time delay between application of laser and application of lightning impulse wave. The order of laser pulse width and also rise and fall time of lightning impulse is very small. Hence a very sophisticated control circuitry is required to control the time delay.

- Experiments can be performed by focusing and non-focusing laser in between the electrodes.

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Composition of the earth's atmospheric air

Constituent	Percent by volume or by Number of molecules of dry air [3]
Nitrogen (N_2)	78.084
Oxygen (O_2)	20.946
Argon (Ar)	0.934
Carbon dioxide (CO_2)	0.031
Neon (Ne)	1.82×10^{-3}
Helium (He)	5.24×10^{-4}
Methane (CH_4)	1.5×10^{-4}
Krypton (Kr)	1.14×10^{-4}
Hydrogen (H_2)	5.00×10^{-5}
Nitrous oxide (N_2O)	3.00×10^{-5}
Xenon (Xe)	8.70×10^{-6}
Carbon monoxide (CO)	1.00×10^{-5}
Ozone (O_3)	Up to 10^{-5}
Water (average)	Up to 1